Int J Life Cycle Assess (2014) 19:1908–1918
DOI 10.1007/s11367-014-0796-0

BUILDING COMPONENTS AND BUILDINGS

Environmental assessment of thermal insulation composite material

Karel Struhala · Zuzana Stránská · Jan Pěnčík · Libor Matějka

Received: 24 February 2014 / Accepted: 1 September 2014 / Published online: 12 September 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract
Purpose This paper presents life cycle assessment of planned mass production of the thermal insulation blocks (TIB) made of thermal insulation composite material (TICM) from secondary raw materials—glass and plastic. This material is being developed at Brno University of Technology, Faculty of Civil Engineering for use in structural details of (especially low energy or passive) buildings subjected to higher compressive loads. Two production modes depending on the quality of the input materials are compared.
Methods The assessment is conducted using GaBi 4 software tool with inbuilt Ecoinvent database. The results of the assessment are presented in individual impact categories according to used characterization model (CML 2001—Dec. 07). All the necessary energy and material flows are specified in detail for the purpose of the assessment. Cut-off allocation method is used for allocating the environmental impacts of recycled materials. Part of the assessment is sensitivity analysis of one variable parameter—amount of TIB produced per year.
Results and discussion The results of the assessment show decisive impact of used electricity source on the overall results—86.2 and 94.3 %, respectively, for both production modes. This is closely connected with quality of used secondary raw materials and design of the production line. Use of higher-quality materials, as well as changes of the designed production line can reduce the overall environmental impacts by almost 30 %.
Conclusions The results show possible improvements in the planned mass production of the TIB. They also find that further investigation will be required before the start of mass production, especially in connection with improving the environmental impacts of used electricity sources.

Keywords Composite plastics · Life cycle assessment · Recycling · Secondary raw materials

1 Introduction

The issue of monitoring the environmental impact of building processes is attracting more and more attention among civil engineers, architects and researchers as the building industry is one of the largest industry sectors. Among other things, it is responsible for 40 % of overall waste production in the EU (Fraunhofer 2009). Some conducted environmental studies monitor only one specific parameter, such as global warming potential (expressed by the amount of CO_2 emissions) or balance of embodied energy—Venkatarama Reddy and Jagadish (2003), Thormark (2002) etc. But to receive an overview of impacts a product can cause to the environment, a more complex assessment is required—e.g. life cycle assessment (LCA). It is a method developed since late 1960s—first study was conducted to assess the environmental, material and energy impacts of a life cycle of packaging for The Coca-Cola Company (Hunt and Franklin 1996). Later, the framework for the LCA was set by international standards of 14 040 series (ISO 2006a, b). Currently, it is used for assessment of environmental impacts of various production systems under various external conditions (e.g. climatic or economic), as can be seen in the works of Anastaselos et al. (2009), Audenaerta et al. (2012) or Utama et al. (2012). But its use in building industry is problematic, because of many uncertainties connected with the construction and operation of a building—the ad-hoc changes of designs, unexpected external factors (e.g. natural disasters) etc. (Hunt and Franklin 1996).

Responsible editor: Guillaume Habert

K. Struhala (✉) · Z. Stránská · J. Pěnčík · L. Matějka
Faculty of Civil Engineering, Institute of Building Structures,
Brno University of Technology,
Veveří 331/95, 602 00 Brno, Czech Republic
e-mail: struhala.k@fce.vutbr.cz

There are studies assessing the whole building, such as study of environmental impacts of 25 commercial buildings in Hong Kong conducted by Chau et al. (2007), which tries to sort used building materials and equipment in accordance with their respective environmental impacts. Other, more common studies address only specific building materials or structures—e.g. Bribián et al. (2011), who compare common building materials and eco-friendly materials; Kim (2011), who assesses the environmental impacts of solar wall systems; Bianchini and Hewage (2012); Stazi et al. (2012); and others. This paper falls into the same group, as it presents results of LCA of planned mass production of thermal insulation blocks (TIB) made of secondary raw materials (Brno University of Technology et al. 2009). The material itself (thermal insulation composite material (TICM)) is developed at Brno University of Technology, Faculty of Civil Engineering, Institute of Building Structures, under the research MSM 0021630511 (Drochytka et al. 2006; Pěnčík et al. 2012). Two different mass production scenarios are assessed and compared. The goal of these assessments is to specify the environmental impacts of the material's mass production, identification of the processes with the greatest share on the overall impacts and proposing optimization of the production process according to the calculated results. The assessment includes all relevant material and energy flows and processes in accordance with the defined goal and scope. The system boundaries include recycling of (secondary) raw materials and the production of the TIB.

2 Methodology

2.1 Definition of goal and scope

It is the first phase of any LCA. It defines depth and range of the assessment, its functional unit, reference flows etc. It also describes the methods and tools used for gathering and subsequent analysis of data. The goal of the assessment presented in this paper is to specify the environmental impacts of planned mass production of the TICM. The functional unit of the assessment is 1,000 TIBs (see Sect. 4). The appropriate reference flow used is the volume of materials and energy consumed during the production of the insulation block. The results of the assessment will be used for the improvements in design, which would make the whole production process more efficient and environmentally friendly.

Because the TICM uses recycled materials, the problem of allocation has arisen. There are several methods of allocation of environmental impacts, which are used in different situations (Baumann and Tillman 2004), and there are still attempts for their improvement or development of new ones—e.g. Kim et al. (1997) proposes an allocation method for cascade recycling. The topic of allocation in the LCA is often discussed in literature—Tillman (2000), Heijungs and Guinée (2007), Cherubini et al. (2011), Spivak and Franchetti (2013) etc.—as the choice of allocation may be decisive for the results of the assessment. For the purpose of the assessment, a cut-off allocation principle (see Fig. 1) is chosen—only materials and energies consumed during the production of the TICM were taken into account. Environmental impacts of the parts of life cycle of the products which are subsequently recycled and used as secondary raw materials for production of TICM, as well as waste management of dismantled TIB are not included in the presented assessment. The main reason for this is that the assessment will be used for improvements of designed production process—environmental impacts of the (secondary) raw materials' production would reduce the share of the impacts of the production process itself on the overall results. Also, high level of uncertainty is connected with these phases of life cycle, which would decrease clarity of the assessment (Kočí 2009; Baker and Lepech 2009)—the environmental impacts of producing the required materials depend on the location of production facility, quality of raw materials, used energy sources, means of transportation and transportation distances etc. (see Sects. 5.2 and 6).

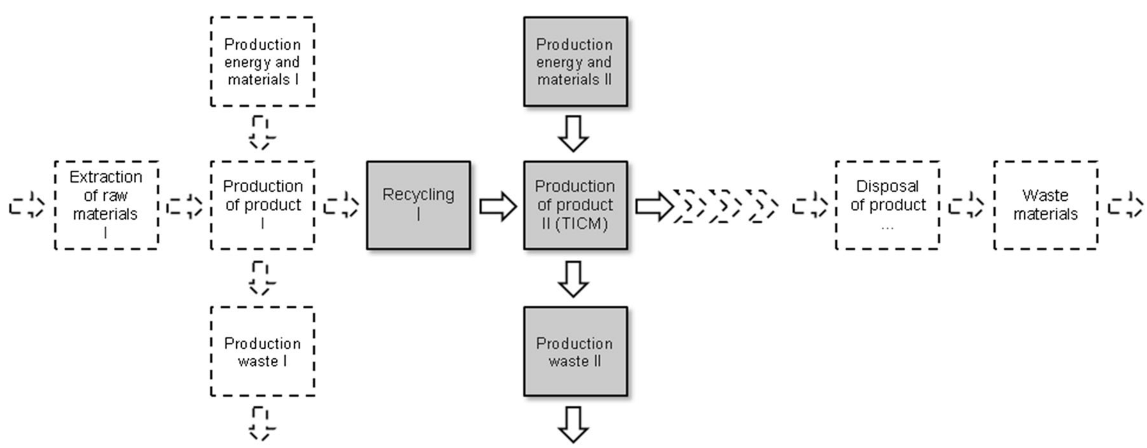

Fig. 1 Diagram showing system boundaries according to used allocation method

2.2 Inventory analysis

During the life cycle inventory (LCI) phase, all the necessary data are gathered in accordance with the depth of the assessment. It is common that authors of the assessment have to predict the events which may occur during the life cycle of the assessed product. In the presented assessment, the LCI phase includes gathering of data about material and energy inputs and outputs needed during the recycling of the raw materials and production of TICM, except for the raw materials themselves (in accordance with the chosen allocation method). As the production line for mass production of TICM does not exist yet, the data for assessment were obtained from operators of similar production line in the Czech Republic. The data about the recycling process of glass and plastic were obtained from an operator of a recycling facility in the Czech Republic. As most of the data are part of their respective production secrets, the operators shared the data under the condition of remaining anonymous; therefore where the reference to the source of data is missing, the data originate from these operators (see Sect. 4). Missing data were taken from literature (Blengini et al. 2012; Scheffler and Colombo 2005; UAB “STIKLOPORAS” 2011).

2.3 Impact assessment (LCIA) and interpretation of results

During the life cycle impact assessment (LCIA) phase, inventory data are aggregated into specific environmental impact categories according to a chosen method. Different LCIA methods will lead to distinct results (values, impact categories and units). LCIA methods can be single-category (e.g. primary energy, exergy and global warming potential) or multi-category, with specific sets of impact categories. Multi-category LCIA methods can be problem- or damage-oriented. Problem-oriented methods (e.g. CML 2001) have midpoint impact categories and model problems at an early stage in the cause–effect chain, allowing a more transparent assessment and limiting of the uncertainties. Damage-oriented methods (e.g. Ecoindicator 99) model the cause–effect chain up to the endpoints (damage to humans and ecosystems), have a narrowed set of categories and have higher uncertainty than midpoint methods (Barnthouse et al. 1998). There are also methods that try to combine both problem- and damage-oriented approaches—e.g. ReCiPe or IMPACT2002+ (Hauschild et al. 2013). They use different impact category indicators to describe the midpoint and endpoint environmental impacts in chosen categories.

Problem-oriented multi-category method CML 2001 (version Dec. 07) developed by the Institute of Environmental Sciences (CML) of Leiden University, Netherlands, is chosen for the presented assessment (Barnthouse et al. 1998). This characterization model presents results using ten impact categories that cover various environmental impacts of human activities (Silva et al. 2013). The assessment is performed using GaBi 4 software tool, which is developed by PE International in Germany (PE International 2014a) . Ecoinvent 2.0 database (Ecoinvent centre 2007) was used as the main source of environmental data for the modelling of the system. This database is maintained and developed by Ecoinvent Centre, Switzerland and is one of the largest available databases of environmental data. GaBi’s own Professional Database (PE International 2014b) was used for completion of the computation model (see Sect. 5).

The results of the assessment are analysed. A sensitivity analysis evaluating impact of changes in production line’s output on the overall results is conducted. The impact of used allocation method on the assessment’s results is also discussed.

3 TICM composition

One of the goals of the research MSM 0021630511 (Drochytka et al. 2006) is the development of new thermally insulating material made of secondary raw materials (Pěnčík et al. 2012). Use of secondary raw materials should decrease environmental impacts of the material life cycle. It should also have a positive impact on the price of the material—secondary raw materials are cheaper and more easily obtained than primary raw materials. Blocks made of this material are intended as a thermal insulation in structural details subjected to high compressive loads, e.g. foundation of the load-bearing walls or the attic walls (Pospíšil et al. 2012).

The composition of the production mixture of the TICM was determined experimentally (Pěnčík et al. 2012). The final mixture uses polypropylene (PP) as a binder and expanded glass (EG) granules as filler. Both materials could be obtained by recycling of municipal or industrial waste. For example, EG granulate may contain up to 80 % of recycled glass (Blengini et al. 2012). The PP is chosen because of its thermal and mechanical properties (tensile modulus E=1,550 MPa, thermal conductivity coefficient λ=0.22 W m^{-1} K^{-1}) (Pěnčík and Matějka 2011; Pěnčík et al. 2013). EG granules of fractions 2–4 and 4–8 mm are used as a thermal insulation component in the TICM. They have density ρ=300 kg m^{-3}, compressive strength σ=2.2 to 2.9 N mm^{-2} and thermal conductivity coefficient λ=0.07 W m^{-1} K^{-1} (LIAVER GmbH & Co. KG 2011). The resulting composite has density ρ=488 kg m^{-3} and thermal conductivity coefficient λ= 0.093 W m^{-1} K^{-1} (Pěnčík et al. 2012; Kalužová et al. 2013).

4 Inventory analysis—TICM production process

This section presents detailed description of TICM production, including description of the recycling process of two

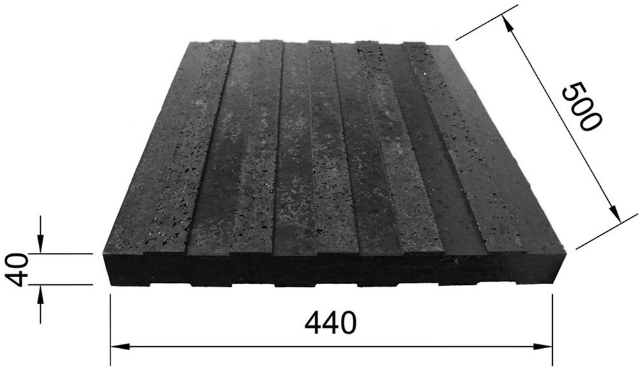

Fig. 2 Prototype of TIB—photography (Struhala et al. 2013)

main compounds—PP and EG granules. The volume of production was set to 2,500 tons of TICM per year. This value represents an estimated maximum output of the production line. It was determined on the basis of information obtained from the operator of similar production line. Weight of 1 TIB (see Fig. 2) is 4.3–2.58 kg of PP and 1.72 kg of EG granules. Therefore, the estimated annual production could reach 581,395 TIBs. The chosen function unit of this assessment is 1,000 TIBs.

4.1 Production of the filler—recycling of waste glass

The filler (EG granules) is the most important compound of TICM. It has the greatest impact on its thermal properties. The raw material for the production of the filler is segregated waste glass (from municipal or technological wastes). A model production line used for the assessment is shown in Fig. 3. This model is based on information from literature (Blengini et al. 2012; UAB "STIKLOPORAS" 2011) and information from an operator of a recycling facility in the Czech Republic. At the beginning of the recycling process, the waste glass has to be cleaned from impurities, such as dirt or remnants of packaging. Otherwise, these impurities could have a negative effect on the properties of the TICM or could cause damage to the production line. At first, the waste glass goes through a detector (3), which detects metals and other materials overlooked during the segregation. Afterwards, the waste glass is crushed into smaller pieces in a shredder (4) and washed in a pressure (water) washer (5) to remove the remains of labels, food etc. To decrease the environmental impact of washing process, the cleaning water is purified and reused (6). Level of reuse of the cleaning water depends on the degree of contamination of the waste glass—in case of heavy contamination the water is reused once at best, whereas in the case of relatively clean technological waste the pressure washing may not be necessary at all. After the washing and drying (7), the glass is milled (8) to a fine powder with individual grains smaller than 5 μm. This glass powder is then mixed (11) with a foaming agent. The mixture is poured into the granulator (12), where the granules of desired shape and size are created. These granules are afterwards burned in a kiln (13) at temperatures which triggers chemical reaction in the foaming agent releasing carbon dioxide (CO_2) and oxygen (O_2). The bubbles of gas are trapped in the structure of the granules, resulting in an increase of their volume, while maintaining the weight. The resulting porous structure has good thermal properties and load-bearing capacity (see Sect. 3).

Estimated output of the recycling line shown in Fig. 3 is 1,000 kg of EG granules per hour. This means that for covering of TICM production of 2,500 tons/year, this recycling line would have to operate for 1,000 h/year—12.5 weeks of 80 working hours. Two modes of operation were assessed. The first mode involves processing of (municipal) waste glass containing impurities which must be removed during the recycling. The second mode involves processing of technological waste glass, which does not require cleaning—the pressure washing and subsequent water purification are therefore not included. Overview of inputs and outputs of both operation modes of EG granules' production can be seen in Tables 1 and 2, while the detailed description is written below.

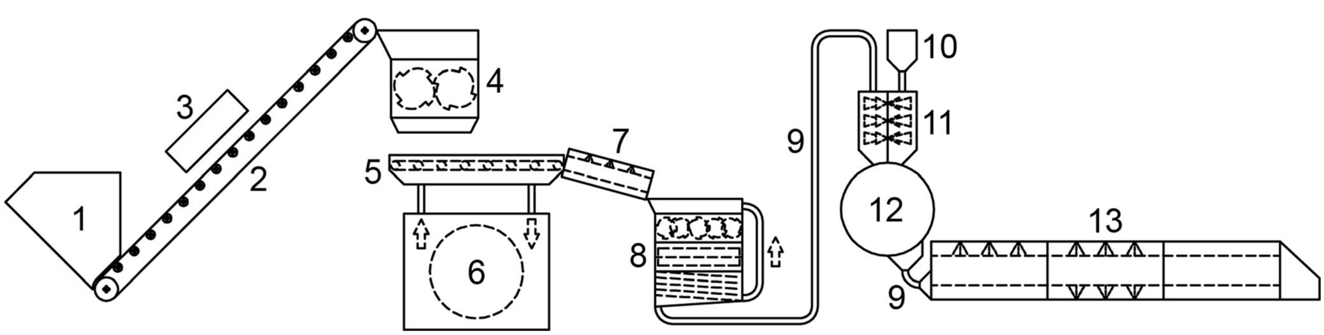

Fig. 3 Diagram of the production line for production of EG granules from waste glass: *1*, waste glass supply; *2*, conveyor belt; *3*, detection and separation of impurities (metals, etc.); *4*, shredder; *5*, pressure washer; *6*, water purifier; *7*, dryer; *8*, mill; *9*, pipeline; *10*, foaming agent supply; *11*, mixer; *12*, granulator; *13*, kiln for burning of EG granules

Table 1 Inputs for the production of EG granules required for production of 1,000 TIBs

1st mode of production			2nd mode of production		
Input	Unit	Quantity	Input	Unit	Quantity
Waste glass	kg	1,764.5	Waste glass	kg	1,649.8
Foaming agent	kg	414.5	Foaming agent	kg	414.4
Electricity	MJ	3,544.8	Electricity	MJ	3,535.9
Machine oil	kg	5.6E−05	Machine oil	kg	4.5E−05
Water	kg	1,466.2	Water	kg	1.7
Aluminium sulphate	kg	3.9	Cleaning agents	kg	3.4E−02
Liquid oxygen	kg	0.9	–	–	–
Cleaning agents	kg	3.4E−02	–	–	–

Based on the available information from literature (Blengini et al. 2012; UAB "STIKLOPORAS" 2011) and the operator of the recycling facility, we calculated that producing the EG granules (needed for production of 1,000 TIBs) using the first mode of operation requires 1,764.5 kg of (municipal) waste glass. This amount of waste glass suffices for producing the required 1,717.9 kg of EG granules. During the recycling process, 279.8 kg of solid wastes (labels, remains of packaging etc.) are removed from the waste glass. The second mode of operation requires 1,649.8 kg of (technological) waste glass to produce the same amount of EG granules. The decrease in the amount of required raw material is caused by the higher purity of technological waste. Accordingly, the amount of solid waste produced during the recycling process decreases to 165.1 kg.

The second material needed for production of EG granules is a foaming agent—mixture of chemicals, which, when heated, releases gasses such as carbon dioxide (CO_2) or oxygen (O_2). Bubbles of these gasses caught in the structure of the material are responsible for its low density. There are different types of foaming agents used for production of EG. In this assessment, we choose adding of mixture of 17.3 kg of calcium carbonate ($CaCO_3$), 17.3 kg of glycerine ($C_3H_8O_3$), 172.7 kg of water (H_2O) and 207.2 kg of liquid glass (Na_2SiO_3) to 1,484.8 kg of washed and milled waste glass (UAB "STIKLOPORAS" 2011).

For the purpose of the assessment, we calculated that overall energy consumption of waste glass recycling and EG granules production would be 3,544.8 MJ (per 1,717.9 kg of EG granules) in the first mode of operation or 3,535.9 MJ in the second mode of operation. The cleaning process consumes less than 1 % of overall energy.

Table 2 Outputs of the production of EG granules required for production of 1,000 TIBs

1st mode of production			2nd mode of production		
Output	Unit	Quantity	Output	Unit	Quantity
EG granules	kg	1,717.9	EG granules	kg	1,717.9
Waste water	kg	1,471.0	Waste water	kg	1.7
Solid waste	kg	279.8	Solid waste	kg	165.1
Carbon dioxide	kg	8.6	Carbon dioxide	kg	8.6

For pressure washing of the waste glass, about 1,466.2 kg of water with addition of 3.9 kg of aluminium sulphate ($Al_2(SO_4)_3$) and 0.9 kg of liquid oxygen (O) are necessary. Regular maintenance and cleaning is considered during the operation of the line. It is estimated that it requires approximately 5.0 kg of machine oil twice a month in the case of the first operation mode (4.0 kg in the case of the second operation mode) and up to 1,000 kg of water with cleaning agents mixed at a ratio of 50:1 at least once per year.

4.2 Production of the binder—recycling of PP

The binder, which connects individual granules of the EG and fills the gaps between them, is the PP. It is a so-called thermoplastic—plastic, which can be almost infinitely remoulded by heat. This fact is used during the recycling of waste PP. Examples of environmental assessment of plastic can be found in literature. Tabone et al. (2010) assesses environmental impacts of production of 12 different polymers from raw materials. Vidal et al. (2009) deals with lessening of environmental impacts of recycled plastic by addition of organic compounds. Arena et al. (2003) addresses recycling of PET or PE packaging in Italy. Figure 4 shows a diagram of model production line used for the assessment as described by the users of similar facilities in the Czech Republic. As in the case of glass recycling, waste PP has to be crushed into smaller pieces in a blade mill (3). Then, it is cleaned from labels and other nonplastic residues in a washer (4). Clean plastic pieces are dried in a pug mill (7) and shredded into chips of desired size in a shredder. Any metal residues are removed from these chips in a metal detector (9). Afterwards, the clean PP chips are heated in a screw extruder (melting temperature of pure PP is about 180 °C), creating a homogenous paste. At the end, the paste is processed into granulate to simplify subsequent manipulation.

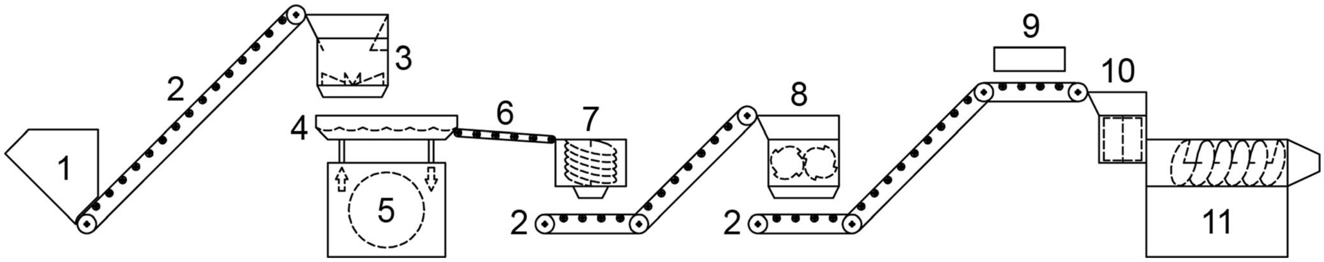

Fig. 4 Diagram of the production line for the production of the PP granules from segregated PP waste. *1*, PP waste supply; *2*, conveyor belt; *3*, blade mill; *4*, washer; *5*, water purifier; *6*, gravity drainage; *7*, pug mill; *8*, shredder; *9*, metal detector; *10*, agglomeration machine; *11*, screw extruder with granulator head

Estimated output of the recycling line described above is 800 kg of PP granules per hour. To cover the requirements of TICM production, it has to operate for 1,875 h/year—23.5 weeks of 80 working hours. Similarly to the EG production line, there are two modes of operation assessed. The first mode involves processing of PP separated from municipal waste, which (as the waste glass) has to be rid of any impurities before further processing. This is done by washing in the water mixed with cleaning agents. The second mode of operation involves processing of technological PP waste, which does not have to be washed. Overview of inputs and outputs of both operation modes of PP recycling and production of PP granules can be seen in Tables 3 and 4.

We calculated that the first mode of production requires 3,172.5 kg of unwashed PP waste for production of 2,576.9 kg of PP granules (needed for the production of 1,000 TIBs). The recycling process produces 596.3 kg of solid waste. The second mode of operation requires 3,013.9 kg of PP waste for the production of required amount of PP granules, while producing 437.6 kg of solid waste.

Calculated energy consumption for production of 2,576.9 kg of PP granules is 11,595.2 MJ in first mode of operation. The PP washing process is responsible for 9 % of overall energy consumption in this mode of operation. Second mode of production consumes 10,480.0 MJ of electricity.

Tap water with cleaning agents is used for washing of PP—approximately 1 kg of water with cleaning agents per 1 kg of waste PP. It is estimated that the operation of the line (the screw extruder, blade mill etc.) requires 160 kg of machine oil for hydraulics or gears. This oil has to be replaced once a year.

Regular maintenance and cleaning of the line is considered similarly to the EG line: The first mode of operation would require 8 kg of machine oil twice a month; the second mode would require 6 kg. Also, cleaning would require 1,000 kg of tap water and cleaning agents once per year. Additionally, the screw extruder has to be cleaned by 100 kg of a mixture of glass shards and PP at least once a year to brush off the sediments stuck inside.

4.3 Production of TIB

For the mass production of TIBs from TICM according to Czech patent no. P303330 (Brno University of Technology 2012), a co-extrusion production line was designed (see Fig. 5). Partially molten PP is extruded from the cartridge (1) on the preheated steel rolls (4). Then, a mixture of EG granules is poured on it from a container (2). Afterwards, it is covered by another layer of partially molten PP from the second cartridge. The second layer of PP fills the gaps between EG granules to ensure integrity of the composite. Shape and size of the produced TIB is moulded by shaped steel rolls. After the moulding, the blocks are cooled (naturally or artificially) to a temperature suitable for further manipulation. TICM is produced continuously. The division into individual blocks is planned with use of spacers (3) inserted in predetermined intervals.

Table 3 Inputs for production of PP granules required for production of 1,000 TIBs

1st mode of production			2nd mode of production		
Input	Unit	Quantity	Input	Unit	Quantity
PP waste	kg	3,172.5	PP waste	kg	3,013.9
Electricity	MJ	11,595.2	Electricity	MJ	10,480.0
Machine oil	kg	1.6E−01	Machine oil	kg	1.2E−01
Water	kg	3,110.7	Water	kg	1.7
Cleaning agents	kg	1.5E−01	Cleaning agents	kg	1.5E−01

Table 4 Outputs of production of PP granules required for production of 1,000 TIBs

1st mode of production			2nd mode of production		
Output	Unit	Quantity	Output	Unit	Quantity
PP granules	kg	2,576.9	PP granules	kg	2,576.9
Waste water	kg	3,559.5	Waste water	kg	1.7
Solid waste	kg	596.3	Solid waste	kg	437.6

Table 5 Inputs required for production of 1,000 TIBs

Input	Unit	Quantity
EG granules	kg	1,717.9
PP granules	kg	2,576.9
Electricity	MJ	9,276.7
Machine oil	kg	2.9E−01
Heating medium	kg	7.4E−01
Glass shards	kg	8.5E−02
Water	kg	9.5E−01
Cleaning agents	kg	4.8E−06

Energy and material consumption of the production line described above were calculated on the basis of information obtained from an operator of similar production line in the Czech Republic. The maximum output of the production line was determined to be 600 kg of TICM per hour. Approximately 10 % of this quantity is unrecyclable waste (scrap, defective pieces etc.). Overview of inputs and outputs of TIB production can be seen in Tables 5 and 6.

It is considered that the production of 1 kg of TICM requires 2.16 MJ of electricity. Therefore, production of 1,000 TIBs requires 9,276.7 MJ of electricity.

The heating of the 18 steel rolls shown in Fig. 5 (including the inlet and outlet pipelines, storage and heating tank for the heating medium) requires 579.6 kg of circulating heating medium—oil. This oil has to be changed periodically, because it degrades slowly. Approximately 20 % of the oil is changed every 3 years. For the lubrication of mechanical parts (gears, bearings etc.) 150 kg of machine oil is required. This machine oil has to be completely replaced every 2 years.

Cleaning of the production line is similar to that of the PP recycling line. The screw extruders for extrusion of PP are cleansed by the mixture of glass shards and PP. This cleaning has to be done before every longer operation outage but at least once per 2 years during the general maintenance of the production line. For regular cleaning, the mixture of 1,000 kg of water and cleaning agents is considered (50:1 ratio) again.

5 Life cycle impact analysis of TIB's production

The goal of the assessment is the identification and quantification of environmental impacts of TIB production. This will help to improve the designed process and also optimise the composition of the TICM. The assessment is performed using GaBi 4 software tool with Professional Database and Ecoinvent 2.0 database installed. The assessment takes into account only the processes, energy and material flows described in the previous section. These had to be assigned to the processes and flows available in the databases. The assignment is shown in Table 7. Because of lack of data in the databases, some simplifications have to be made.

Two modes of recycling of raw materials (with and without wet cleaning), as described above, are considered in the assessment. These variants represent two extremes with the highest and the lowest environmental impacts.

The gathered data were processed with use of CML 2001—Dec. 07 characterization model (Barnthouse et al. 1998). This characterization model was developed by the Institute of Environmental Sciences in Leiden, Netherlands. The used model presents results of the assessment in 10 impact categories, with use of so-called indicators, and their equivalent units (see Table 8). These are used to show what amount of reference substance has the same environmental impact as the assessed material—thus enabling comparisons of completely different materials and processes.

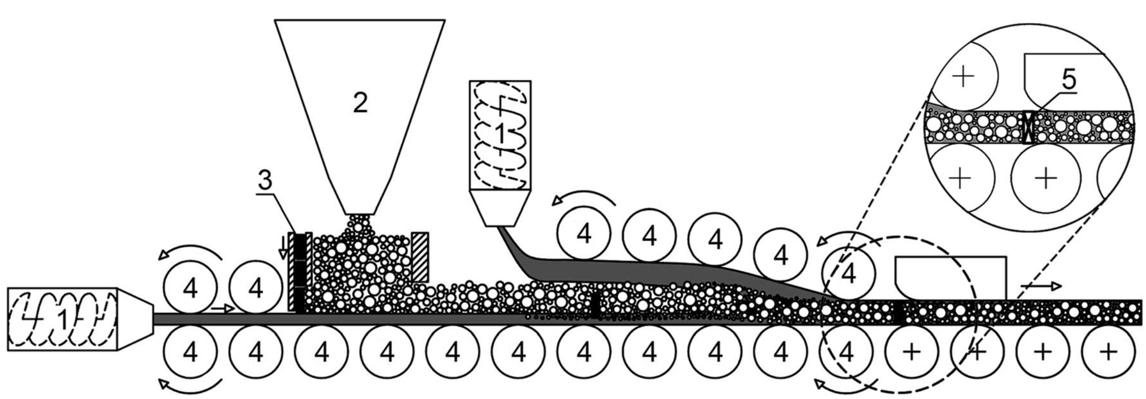

Fig. 5 Diagram of the TICM/TIB production line: *1*, PP cartridge equipped with a screw extruder; *2*, EG container; *3*, insertion of spacers; *4*, preheated steel rolls; *5*, spacer (Brno University of Technology 2012)

Table 6 Outputs of production of 1,000 TIBs

Output	Unit	Quantity
TICM block	Pieces	1
Waste water	kg	9.54E−04
Solid waste	kg	500.0

Because of different equivalent units, it is impossible to compare the results of different impact categories. Therefore, normalisation and weighting has to be done. The normalisation converts results obtained in each impact category into a dimensionless value. Afterwards, these values have to be weighted, because different impact categories have different overall impact on the environment. CML 2001—Dec. 07, EU25+3 normalisation incorporated in the GaBi 4 was used for this purpose.

Comparison of both production modes (Table 9) shows that the environmental impact of the second mode (without the wet cleaning of waste glass and PP) is 34.7 % (average value) lower than the environmental impacts of the first production mode. The highest difference can be observed in TETP category (85.7 %), while the lowest difference can be observed in GWP category (4.7 %). This is caused by lack of the washing of raw materials and all processes and flows connected to it in the second mode of production.

Table 10 shows normalised results of the assessment. It also shows shares the individual impact categories have on the overall environmental impacts. We can see differences in the distribution of the environmental impacts into individual categories for both production modes. For example, TETP has six times higher share in the overall results in the first mode of production,than in the second mode. As mentioned above, this is caused by different amounts of inputs and outputs required for both production modes.

Table 7 Matching of data gathered during the LCI phase with data available in the database

LCI entry	Database entry
Aluminium sulphate	RER: aluminium sulphate, powder, at plant
Carbon dioxide	Carbon dioxide (Inorganic emissions to air)
Cleaning agents	RER: soap, at plant
Electricity	CZ: Powermix
Foaming agent	CH: limestone, milled, loose, at plant
	RER: glycerine, from rape oil, at esterification plant
	RER: tap water, at user
	RER: sodium silicate, spray powder 80 %, at plant
Glass sharp	RER: glass, cullets, sorted, at sorting plant
Heating medium	RER: lubrication oil, at plant
Machine oil	RER: lubrication oil, at plant
Liquid oxygen	RER: oxygen, liquid, at plant
Solid waste	RER: Landfill for inert matter (unspecific construction waste) PE
Waste water	RER: Wastewater treatment (contains organic and inorganic load) PE
Water	RER: tap water, at user

Table 8 List of impact categories used in CML 2001—Dec. 07 characterization model

Impact category	Unit
Abiotic Depletion (ADP)	kg Sb-Eq.
Acidification Potential (AP)	kg SO_2-Eq.
Eutrophication Potential (EP)	kg Phosphate-Eq.
Freshwater Aquatic Ecotoxicity Potential (FAETP inf.)	kg DCB-Eq.
Global Warming Potential (GWP 100 years)	kg CO_2-Eq.
Human Toxicity Potential (HTP inf.)	kg DCB-Eq.
Marine Aquatic Ecotoxicity Potential (MAETP inf.)	kg R11-Eq.
Ozone Layer Depletion Potential (ODP, steady state)	kg Ethene-Eq.
Terrestric Ecotoxicity Potential (TETP inf.)	kg DCB-Eq.

5.1 Sensitivity analysis

To analyse, if the environmental impact will be influenced by the change of production volume, a sensitivity analysis is conducted. The range of production volume was set between 2,500 and 1,145.3 tons of TICM per year. The higher value represents the estimated maximum output of TICM/TIB production line, while the lower value is volume of TICM required for production of 240,000 TIBs, which is the lowest production level set during the original development of the material. The sensitivity analysis is conducted in 20 steps in the set interval, using the GaBi 4 tool and CML 2001—Dec. 07 characterization for all 20 steps.

The analysis shows that change of production volume has minimal impact on overall results of the assessment. The

Table 9 Results of the environmental impact assessment of both TICM/TIB production modes (for production of 1,000 TIBs)

Impact category	Unit	1st mode of production	2nd mode of production
ADP	kg Sb-Eq.	35.8	31.4
AP	kg SO_2-Eq.	41,904	41,808
EP	kg phosphate-Eq.	41,732	41,821
FAETP inf.	kg DCB-Eq.	1,259.5	572.1
GWP (100 years)	kg CO_2-Eq.	5,813.3	5,541.5
HTP inf.	kg DCB-Eq.	1,196.2	839.3
MAETP inf.	kg DCB-Eq.	3,750,703.1	3,233,603.2
ODP (steady state)	kg R11-Eq.	1.8E−04	1.3E−04
POCP	kg ethene-Eq.	41,792	41,640
TETP	kg DCB-Eq.	333.6	47.8

Table 10 Normalised (CML 2001—Dec. 07, EU25+3 normalisation) results of the environmental impact assessment of both TICM/TIB production modes (for production of 1,000 TIBs)

Impact category	1st mode of production		2nd mode of production	
	(−)	(%)	(−)	(%)
ADP	2.12E−09	2.22	1.86E−09	2.23
AP	1.37E−09	1.43	1.10E−09	1.33
EP	1.85E−10	0.19	9.40E−11	0.11
FAETP inf.	2.46E−09	2.58	1.12E−09	1.34
GWP (100 years)	1.12E−09	1.17	1.06E−09	1.28
HTP inf.	1.18E−10	0.12	8.31E−11	0.10
MAETP inf.	8.43E−08	88.23	7.72E−08	92.60
ODP (steady state)	2.28E−11	0.02	1.71E−11	0.02
POCP	9.84E−10	1.03	4.15E−10	0.50
TETP inf.	2.88E−09	3.01	4.12E−10	0.49

difference between the bordering results (2,500 and 1,145.3 tons of TICM produced) is approximately 0.12 % in favour of the higher production volume. This result was expected, due to the chosen allocation method and functional unit.

5.2 Comparison with other materials

Comparing the TICM with other insulation materials with similar use is out of scope of this paper. There is a lot issues connected with such comparisons. But nevertheless, it is crucial for the further development of the material. Thus, a short outline of the encountered difficulties is presented below.

Of other thermal insulation materials, the foam glass has most similar mechanical properties (PE International 2008) and use (structural details exposed to high compressive loads). Therefore, it is (to a certain extend) comparable with TICM. Unfortunately, no Environmental Product Declaration (EPD according to ISO 14 025; ISO 2006c) or other similar documentation of environmental impacts (localised for Czech Republic) of foam glass' production is currently publicly available. This means that we can compare only with data localised for other countries available in EPDs (PE International 2008) or in the used LCI databases—with different energy supply mixes, transportation options etc. The Ecoinvent 2.0 database for example contains three different datasets for foam glass: *AT*: *foam glass*, *at regional storage*; *CH*: *foam glass*, *at regional storage*; *RER*: *foam glass*, *at plant*. Environmental impacts specified by these datasets vary by tenths of percents, depending on chosen impact category. Results in the MAETP category defined in CML 2001—Dec. 07 characterization model vary by more than 60 %, while results in TETP category (using the same characterization) varying by less than 5 %. Such uncertainty reduces the accuracy of any comparison (as mentioned in Sect. 2.1).

Another issue connected with comparing TICM (or TIBs) with other products is end-of-life management. Foam glass blocks used in the same way as TIBs, such as FOAMGLAS® PERINSUL SL (PE International 2008), are coated with a thin layer of bitumen that closes the surface pores. When this bituminous layer is removed (with a part of foam glass), the rest of the foam glass block can be completely recycled. Recycling of TICM in the same way would require more energy than the original production, as both components would have to be separated (e.g. by melting and filtration) before reuse on the TICM production line. Otherwise, the thermal properties of the TIBs would decrease with each remoulding, because of uneven distribution of the EG granules. But thanks to their mechanical properties, the TIBs should withstand the long-term installation in the structural details of the building without significant changes in shape or structure. Therefore at the end-of-life of the building, they could be removed, disconnected and reused (after cleaning) easily. Long-term load testing of TIBs' dimensional stability is underway now.

Also, even though we said that foam glass has the most similar mechanical properties, these two materials still differ significantly. While the foam glass has lower thermal conductivity ($\lambda_{PERINSUL}$=0.055 W m^{-1} K^{-1} vs. λ_{TICM}= 0.093 W m^{-1} K^{-1}) and is lighter ($\rho_{PERINSUL}$=200 kg m^{-3} vs. ρ_{TICM}=488 kg m^{-3}), the TICM has higher load-bearing capacity—TICM'S compressive strength was tested up to 10 MPa, while the FOAMGLAS® PERINSUL SL has a compressive strength of approximately 3 MPa. This means that finding a common function for comparison is a bit difficult. If we would compare the materials, for example, by the volume required to provide the same thermal resistance of the insulated structure, the foam glass would be the undisputed victor of the comparison—see Table 11, comparing a plate of FOAMGLAS® PERINSUL SL (PE International 2008) with second production mode of TIBs. Such comparison does not take into account all the properties of TICM, but it can still serve as a basis for further improvements of the TICM's composition.

Table 11 Comparison of environmental impacts of 1×1 m desks made of TICM and foam glass in thicknesses necessary for providing the *U* value 0.5 m^{-2} K W^{-1}

Impact category	Unit	TICM	PERINSUL SL
AP	kg SO_2-Eq.	3.92E−01	4.52E−02
EP	kg phosphate-Eq.	3.67E−02	5.06E−03
GWP (100 years)	kg CO_2-Eq.	117.13	23.34
ODP (steady state)	kg R11-Eq.	2.78E−06	1.89E−07
POCP	kg ethene-Eq.	2.33E−02	3.96E−03

Impact categories chosen according to environmental data of FOAMGLAS PERINSUL written in the EPD (International 2008)

6 Discussion and conclusions

The goal of the assessment presented in this paper is the optimization of the planned mass production of insulation blocks made of secondary raw materials. For this purpose, we used LCA methodology described in literature (Baumann and Tillman 2004) as the most precise assessment method available. The allocation method chosen for the assessment is best suited for this, as it does not take into account the actual raw materials (see Fig. 1), only the inputs and outputs connected with the operation of the recycling and production lines and with transformation of the raw materials into the final product. The results of the assessment are shown in Tables 9 and 10. They show that the electric energy required for the recycling and production processes has the greatest impact on the overall results (86.2 and 94.3 %, respectively—see Table 12). This is at least partially caused by the database entry *CZ*: *Powermix*, used in the assessment. It should represent the average environmental impacts of energy production in the Czech Republic. The most electricity in Czech Republic (approximately 52 % in 2012 according to Energy Regulatory Office-Department of Statistics 2013) is produced by thermal power plants burning coal; therefore, the environmental impacts of the *CZ*: *Powermix* entry are rather high. If a different source or electricity with smaller environmental impacts or different database entry is used (e.g. Powermix from different country), it would have major impact on the results of the assessment (and also the results of the comparison presented in Table 11). Another option is the use of renewable energy sources producing electricity directly for the production facility—the best (most stable and efficient) would be a small run-of-the-river power plant. But such changes are out of scope of this paper. The production of the material is planned in Czech Republic, but the exact location is not defined yet. Regarding the assessed production process, there are two main ways of reducing the environmental impacts of overall energy consumption. The first one is to use more efficient machinery. The assessment of this kind of improvement would require more specific data from the operators and producers of the machines. The other way of improvement is to simplify the production process—specifically to combine the TICM production line with the PP recycling line. This would eliminate the need for granulation and subsequent re-melting of PP, decreasing the overall electricity consumption by approximately 30 %. As the electricity consumption has the highest share in overall environmental impacts, this would greatly improve the results of the assessment.

Table 12 Flows with the highest share (shown in percents) of the overall environmental impact of TICM production

Input/output	1st mode of production (%)	2nd mode of production (%)
Electricity	86.2	94.3
Foaming agent	4.9	5.6
Cleaning agents+water	8.8	–

The assessment also shows that there is a big difference between the two described recycling technologies. In other words—the purity of the raw material (glass or PP waste) can greatly affect the overall environmental impact of TICM production—the cleaner the raw material, the lesser the impact. Cleaning agents and water used for washing of impurities are responsible for almost 9 % of overall environmental impacts—see Table 12. But the changes in the washing process or quality of supplied raw materials have to be made cautiously, because the influence of chosen boundary conditions on the assessment has to be taken into account. Also, it is likely that higher quality raw materials, considered for the second mode of production would have a negative impact on overall operating costs. This would increase the price of the TIB, thus reducing its competitiveness in comparison to other materials. Verification of accuracy of proposed suggestions, as well as design and assessment of other possible improvements, such as the choice of different foaming agent, etc. will require further experiments.

Acknowledgements Presented assessment was conducted with support of the grant FAST-S-14-2418 of Brno University of Technology, Faculty of Civil Engineering.

References

Anastaselos D, Giama E, Papadopoulos AM (2009) An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. Energ Buildings 41:1165–1171

Arena U, Mastellone ML, Perugini F (2003) Life cycle assessment of a plastic packaging recycling system. Int J Life Cycle Assess 8:92–98

Audenaerta A, De Cleynb SH, Buylea M (2012) LCA of low-energy flats using the Eco-indicator 99 method: impact of insulation materials. Energ Buildings 47:68–73

Baker JW, Lepech M (2009) Treatment of uncertainties in life cycle assessment. Stanford University http://www.stanford.edu/~mlepech/pubs/icossar.lca.uncertainty.09.pdf. Accessed 12 December 2013

Barnthouse L, Fava J, Humphreys K, Hunt R, Laibson L, Noesen S et al (1998) Life cycle impact assessment: the state-of-the-art. SETAC Press, Pensacola

Baumann H, Tillman A-M (2004) The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application. Studentlitteratur, Lund

Bianchini F, Hewage K (2012) How "green" are the green roofs? Lifecycle analysis of green roof materials. Build Environ 48:57–65

Blengini GA, Busto M, Fantoni M, Fino D (2012) Eco-efficient waste glass recycling: integrated waste management and green product development through LCA. Waste Manage 32(5):1000–1008

Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46:1133–1140

Brno University of Technology (2012) Koextruzní penetrační linka pro výrobu vysoce plněných kompozitních desek a způsob jejich výroby (Co-extrusion penetration line for highly filled composite panels and their production method). Originator of the copyright certificate: L. Matějka, J. Pěnčík, J. Kučera, Industrial Property Office, Czech Republic, P 303330, 2012-08-01, Czech patent

Brno University of Technology, Faculty of Civil Engineering, Institute of Building Structures (2009) Dämblockelelement zur Unterbrechung von Wärmebrücken im Fussbereich des Mauerwerks (Insulation block element for interrupting thermal bridges in the transition area between a wall and a foundation). Inventor: L. Matějka, J. Šinogl, J. Pěnčík, European Patent Office-EPO, EP 1918471, 2009-08-05, EU patent

Chau CK, Yik FWH, Hui WK, Liu HC, Yu HK (2007) Environmental impacts of building materials and building services components for commercial buildings in Hong Kong. J Clean Prod 15:1840–1851

Cherubini F, Stromman AH, Ulgiati S (2011) Influence of allocation methods on the environmental performance of biorefinery products—a case study. Resour Conserv Recy 55:1070–1077

Drochytka R et al (2006) MSM0021630511—progressive building materials with utilization of secondary raw materials and their impact on structures durability. Brno University of Technology, Brno

Ecoinvent Centre (2007) Ecoinvent v2.0. Swiss Centre for Life Cycle Inventories, Switzerland

Energy Regulatory Office-Department of Statistics (2013) Roční zpráva o provozu ES ČR 2012. http://www.eru.cz/user_data/files/statistika_elektro/rocni_zprava/2012/RZ_elektro_2012_v1.pdf. Accessed 5 February 2014

Fraunhofer ISI (2009) Study on the energy savings potentials in EU Member States, Candidate Countries and EEA Countries final report. Fraunhofer-Institute for Systems and Innovation Research (Fraunhofer ISI; Coordinator), Karlsruhe/Grenoble/Rome/Vienna/Wuppertal

Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, Schryver AD, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess 18(3): 683–697

Heijungs R, Guinée JB (2007) Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. Waste Manage 27: 997–1005

Hunt RG, Franklin WE (1996) LCA—how it came about: personal reflections on the origin and LCA in the USA. Int J Life Cycle Assess 1(3):147–150

ISO (2006a) Environmental management—life cycle assessment—principles and framework (ISO 14040: 2006). International Organization for Standardization (ISO), Geneva

ISO (2006b) Environmental management—life cycle assessment—requirements and guidelines (ISO 14044: 2006). International Organization for Standardization (ISO), Geneva

ISO (2006c) Environmental labels and declarations—type III environmental declarations—principles and framework (ISO 14025: 2006). International Organization for Standardization (ISO), Geneva

Kalužová A, Pěnčík J, Matějka L, Matějka L, Pospíšil T (2013) Thermal insulation composite material based on polymers—determination of thermal conductivity. Int J Civil Eng Environ Eng 35(2):1176–1180

Kim K-H (2011) A comparative life cycle assessment of a transparent composite facade system and a glass curtain wall system. Energ Buildings 43:3436–3445

Kim S, Hwang T, Lee KM (1997) Allocation for cascade recycling system. Int J Life Cycle Assess 2:217–222

Kočí V (2009) Posuzování životního cyklu—LCA. Ekomonitor, Chrudim

LIAVER GmbH & Co. KG (2011) Prozatímní technický list. http://www.liaver.cz/repository/tds_Liaver_4-8_mm_CZ.pdf. Accessed 9 November 2013

PE International (2008) Environmental Product Declaration according to ISO 14 025 FOAMGLAS®. Institut Bauen und Umwelt e. V., EPD-PCE-2008111-E, 15-10-2008. http://www.pe-international.com/uploads/media/IBU_Declaration_Foamglas.pdf. Accessed 12 May 2014

PE International (2014a) GaBi Software—to drive product sustainability!. http://www.gabi-software.com/software/gabi-software/. Accessed 5 February 2014

PE International (2014b) Professional Database. http://www.gabi-software.com/databases/gabi-databases/professional/. Accessed 5 February 2014

Pěnčík J, Matějka L (2011) FEA analysis and monitoring of long-term behavior of an insulation block from recycled polymer HDPE. Adv Mater Res 320:363–368

Pěnčík J, Matějka L, Kalužová A, Matějka L, Dostálová D, Pospíšil T (2012) Development of thermal insulation composite material from recycled polymer and recycled glass. Adv Mater Res 487:701–705

Pěnčík J, Matějka L, Matějka L (2013) Thermal and static analysis of an insulation block from recycled polymer HDPE for solution of thermal bridges in wall-footing detail. Key Eng Mat 525–526:473–476

Pospíšil T, Pěnčík J, Matějka L, Matějka L, Kalužová A, Dostálová D (2012) Elimination of thermal bridge by thermal insulation composite material. Adv Mater Res 482–484:1654–1659

Scheffler M, Colombo P (2005) Cellular ceramics: structure, manufacturing, properties and applications. Wiley-VCH Verlag GmbH & Co, Weinheim

Silva DAL, Mendes NC, Varanda LD, Ometto AR, Lahr FAR (2013) Life cycle assessment of urea formaldehyde resin: comparison by CML (2001), EDIP (1997) and USEtox (2008) Methods for toxicological impact categories. In: Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Springer, Singapore, pp 529–534

Spivak A, Franchetti M (2013) A comparison of allocation methods for hybrid life cycle assessments. Int J Environ Eng Res 2(1):1–17

Stazi F, Mastrucci A, Munafò P (2012) Life cycle assessment approach for the optimization of sustainable building envelopes: an aplication on solar wall systems. Build Environ 58:278–288

Struhala K, Stránská Z, Matějka L, Pěnčík J (2013) Environmental assessment of production of thermal insulation block from secondary raw materials. Adv Mater Res 683:444–450

Tabone M, Cregg J, Beckman E, Landis A (2010) Sustainability metrics: life cycle assessment and green design in polymers. Environ Sci Technol 44:8264–8269

Thormark C (2002) A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Build Environ 37:429–435

Tillman A-M (2000) Significance of decision-making for LCA methodology. Environ Impact Assess 20:113–123

UAB "STIKLOPORAS" (2011) Granulated Foam Glass Production System. Inventor: V. V. Jegorov, S. B. Rodin, S. S. Rodin, World Intellectual Property Organization, WO 2011/061569 A1, 2011-05-26, International patent

Utama NA, Mclellan BC, Gheewala SH, Ishihara KN (2012) Embodied impacts of traditional clay versus modern concrete houses in a tropical regime. Build Environ 57:362–369

Venkatarama Reddy BV, Jagadish KS (2003) Embodied energy of common and alternative building materials and technologies. Energ Buildings 35:129–137

Vidal R, Martínez P, Garraín D (2009) Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters. Int J Life Cycle Assess 14:73–82